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Jet Propellant 8 versus Alternative Jet Fuels

A Life-Cycle Perspective

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The Air Force is the largest user of jet fuel in [the Department of Defense (DOD)], consuming 2.4 billion gallons per year."[1] In light of environmental impacts associated with using nonrenewable fuel sources and national security concerns regarding dependency on foreign oil, it is no surprise that the United States is paying more attention to alternative fuels. Both DOD and Air Force energy strategies address the need to develop and produce such fuels. The DOD has made a commitment to energy security, establishing an energy initiative that "strive[s] to modernize infrastructure, increase utility and energy conservation, enhance demand reduction, and improve energy flexibility, thereby saving taxpayer dollars and reducing emissions that contribute to air pollution and global climate change."[2] This initiative has the following four goals:

1. Maintain or enhance *operational effectiveness* while reducing total force energy demands
2. Increase energy strategic *resilience* by developing alternative/assured fuels and energy
3. Enhance operational and business effectiveness by *institutionalizing energy considerations* and solutions in DoD *planning & business processes*
4. Establish and monitor Department-wide energy *metrics* (italics in original)[3]

In concert with the DOD's efforts, the Air Force's energy initiative features a complementary vision: "Make Energy a Consideration in All We Do."[4] The following three components of the Air Force's strategy reflect this vision:

1. *Reduce Demand* - Increase our energy efficiency through conservation and decreased usage, and increase individual awareness of the need to reduce our energy consumption.
2. *Increase Supply* - By researching, testing, and certifying new technologies, including renewable, alternative, and traditional en-

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ergy sources, the [US]AF can assist in creating *new domestic supply* sources.

3. *Culture Change* - The Air Force must create a culture where all Airmen make energy a consideration in everything they do, every day (italics in original).[5]

This article addresses the second component of the Air Force's strategy and the following specific goal: "By 2016, be prepared to cost competitively acquire 50% of the Air Force's domestic aviation fuel requirement via an alternative fuel blend in which the alternative component is derived from domestic sources produced in a manner that is 'greener' than fuels produced from conventional petroleum."[6] Several questions arise with regard to this goal. Granted, procuring "greener" fuels is a noble aspiration, but how do we evaluate such a fuel appropriately? What does the term *greener* actually mean in this situation? How do we evaluate whether a proposed biofuel is greener than the jet propellant 8 (JP-8) the Air Force currently uses? To answer these questions, this article takes a life-cycle perspective since many modern systems are complex and comprised of interdependent processes and activities. The article thus provides relevant background material regarding biofuels and applies the Economic Input-Output Life Cycle Assessment (EIO-LCA) methodology to compare petroleum-derived jet fuel (i.e., JP-8) to an alternative jet fuel derived from a coal-biomass-to-liquid (CBTL) process. The EIO-LCA approach compares the global warming potential (GWP) of those two fuel types over their entire life cycles. The EIO-LCA results give Air Force leaders a basis for evaluating alternative ways of implementing the service's energy strategy.

Background

Before presenting and discussing the EIO-LCA results, the article addresses environmental concerns associated with burning fuel; defines and characterizes the different types of alternative fuels, including the Air Force's proposed alternative fuel; and then describes life-cycle assessments (LCA).

Environmental Concerns

Greenhouse gases (GHG) trap heat in the earth's atmosphere. According to the Energy Information Administration, "These gases allow sunlight to enter the atmosphere freely. When sunlight strikes the Earth's surface, some of it is re-radiated back towards space as infrared radiation (heat). Greenhouse gases absorb this infrared radiation and trap its heat in the atmosphere."[7] Some GHGs occur naturally, but man-made sources tend to increase the levels of these gases. Carbon-dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases are the principal GHGs that enter the earth's atmosphere because of human activities, primarily as the result of the combustion of fossil fuels.[8]

Alternative Fuel

According to the DOD, "The term 'alternative' fuel is used to differentiate between diesel-type jet fuel produced from crude oil and synthetic fuel produced from non-crude oil. An alternative fuel should emulate the baseline fuel's properties to increase fungibility within military assets."[9] To be certified, alternative fuels must emulate the properties of JP-8 (i.e., yield the same energy output per unit) to ensure no degradation of flight safety.

The Air Force's alternative-fuel program seeks to produce a 100 percent "drop-in" hydrocarbon jet fuel or jet fuel blend stock. The term *drop-in* indicates that the fuel is fully interchangeable with current aviation fuels in both performance and handling so that flight safety does not degrade in any way. Typically, a blend stock consists of a 50 percent mixture of hydrocarbon (alternative fuel) and a petroleum-derived aviation fuel.[10] Regardless of their drop-in or blended status, alternative fuels are typically developed from biomass. Researchers are currently investigating three primary types of

biomass to produce ground-vehicle fuels and jet fuels: sugars and starches, fats and oils, and “lingocellulosic” material. Corn is an example of a starch widely used for the production of ethanol in the United States; however, we cannot use ethanol for jet fuel because of its low flash point and heat of combustion.[11] From triglycerides—fats from oilseeds—we frequently produce biodiesel, a fuel appropriate for ground vehicles but not aircraft. Finally, switchgrass represents a lingocellulosic biomass used to produce aviation fuel. Our analysis focuses on fuels derived from this type of biomass.

Experts still debate whether biofuels are better for the environment than traditional petroleum-derived fuels. Opponents of the former consider them detrimental to the environment. For example, Timothy Searchinger, a biofuel research scholar at Princeton University’s Woodrow Wilson School, notes that “previous accountings [analyses] were one-sided because they counted the carbon benefits of using land for biofuels but not the carbon costs, the carbon storage, and sequestration sacrificed by diverting land from its existing uses.”[12] If current forests or grasslands are converted to cropland to produce biofuel, the conversion releases into the atmosphere carbon previously stored in trees and other plants.

Proponents of biofuels assert that producing them from biomass will result in a carbon credit. Bent Sørensen, a biofuel researcher at Roskilde University of Denmark, disagrees with Searchinger, contending that “Searchinger suggests . . it would be more scholarly to account for all carbon assimilation and release as a function of time rather than just consider biomass carbon neutral. Some of the same authors recently attacked ‘second-generation’ biofuels, making the prediction that biofuels will soon be derived entirely from cellulosic materials grown on marginal land.” Sørensen further argues that cellulosic materials will come from residues of existing biomass-cultivation operations already functioning around the world, thereby not creating additional carbon emissions.[13]

Our analysis considered switchgrass as the biomass portion of the CBTL jet fuel. We assume that switchgrass comes from marginal or degraded lands and does not fit into the category described by Searchinger as a land-use change to produce cellulosic biomass.[14] Therefore, we assigned a carbon credit to the switchgrass portion of the CBTL jet fuel. According to a University of Dayton Research Institute report, one can take a 15 percent credit on the GHGs emitted by switchgrass when performing an LCA using biomass to produce Fischer-Tropsch (FT) jet fuels.[15] The FT process converts carbon monoxide (CO) and hydrogen (H_2) derived from coal, natural gas, or biomass into liquid fuels such as diesel or jet fuel. The research institute’s report gives a GHG credit for switchgrass of 50 to 100 kilograms of CO_2 equivalents per ton of biomass.[16] This information is vital in conducting an LCA.

Life-Cycle Assessment

An LCA is a holistic analytical technique for assessing environmental effects throughout the life cycle of any product, process, or activity. In its purest form, the evaluation begins with the initial extraction of raw materials from the earth and ends once all materials are returned to the earth. Typically referred to as a cradle-to-grave approach, the life cycle includes five phases (fig. 1). These types of life-cycle approaches “help us to find ways to generate the energy we need without depleting the source of that energy and without releasing greenhouse gases that contribute to climate change.”[17]

LCA models are thus important tools that facilitate green design methods for various types of projects.[18] They also provide decision makers additional information that helps define the environmental effects of activities and identify opportunities for improvements. Although numerous LCA variants exist, there are three basic types of models: process-based, EIO, and hybrid. These models typically use similar inventories of environmental emissions and resources to determine the environmental burden cor-

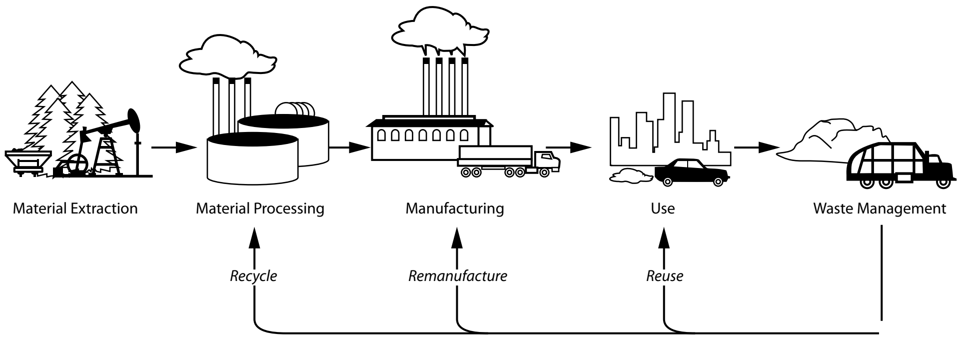

Figure 1. Life-cycle assessment phases. (Reprinted from Congress of the United States, Office of Technology Assessment, *Green Products by Design: Choices for a Cleaner Environment* [Washington, DC: Congress of the United States, Office of Technology Assessment, September 1992], 4.)

responding to any product, process, or activity. However, EIO-LCA models are usually considered more advantageous if application cost, feedback flow, or speed of analysis is important.[19]

Process-Based Life-Cycle Assessment. A process-based LCA breaks down a product or service into smaller pieces and traces each piece back to its origin. This type of LCA offers precise environmental impacts of a product or service. However, two challenges accompany process-based LCAs: the analysis boundary and circularity effects. Because of the difficulty of capturing an entire process and all of its subprocesses, researchers must take great care to determine the boundaries of what they will exclude from the analysis. Circularity effects mean that it takes a lot of "stuff" to make other "stuff." For example, "to make the paper cup requires steel machinery. But to make the steel machinery requires other machinery and tools made out of steel. And to make the steel requires machinery, yes, made out of steel. Effectively, one must have completed a life cycle assessment of all materials and processes before one can complete a life cycle assessment of any material or process."[20]

Economic Input-Output Life-Cycle Assessment. The EIO approach incorporates economic data from the US Bureau of Economic Analysis and environmental data from both the Environmental Protection Agency and Department of Energy. The EIO-LCA model is based on Wassily Leontief's Nobel Prize–winning EIO model.[21] According to Chris Hendrickson, a Carnegie Mellon University engineering professor,

> Leontief proposed a general equilibrium model that requires specifying the inputs that any sector of the economy needs from all other sectors to produce a unit of output. His model is based on a simplifying assumption that increasing the output of goods and services from any sector requires a proportional increase in each input received from all other sectors. The resulting EIO matrix has presently been estimated for developed nations and many industrializing economies.[22]

The EIO-LCA model uses EIO matrices and industry-sector-level environmental and resource consumption data to assess the economy-wide environmental impacts of products and processes.[23] The approach simplifies the complex nature of LCAs by using mathematical formulas to convert the monetary transactions between industry sectors into their environmental impacts.[24] EIO-LCA models identify direct, indirect, and total environmental effects due to production and consumption of goods and services. Total effects are the sum of direct and indirect effects.[25]

Hybrid Life-Cycle Assessment. A hybrid model integrates a process-based LCA

with the EIO-LCA to produce more accurate information from an item or process; when information is not available, one can use the EIO-LCA. For example, one may know the environmental impact of the use phase of a paper cup but not the impact of the extraction phase. In that case, analysts could use the specific information for the use phase and then employ the EIO-LCA model to estimate information for the other phases. Our analysis used a hybrid LCA model.

Determining a Fuel's "Greenness"

In January 2009, the Department of Energy reported that CBTL fuels can compete economically with current petroleum-derived fuels. Specifically, a CBTL process using a mixture of 8 percent (by weight) biomass and 92 percent (by weight) coal can produce economically competitive fuels when crude oil prices equal or exceed $93 per barrel. Furthermore, CBTL fuels have 20 percent lower life-cycle GHG emissions than petroleum-derived ones. Even if CBTL is not economically competitive, the report noted that CBTL fuel has two clear advantages: (1) it has lower GHG emissions, and (2) it can be produced from domestic sources, thereby limiting the amount of foreign crude oil the United States imports.[26]

The CBTL process uses three existing technologies to convert coal and biomass into liquid fuel: gasification, FT synthesis, and carbon capture and storage. Gasification converts coal and biomass into CO and H_2, a mixture commonly referred to as "syngas." FT synthesis applies heat and pressure to syngas in the presence of a catalyst such as cobalt to create a liquid fuel.[27] The resulting CO_2 by-product is captured and stored through a relatively inexpensive process known as carbon sequestration, which promotes the alternative fuel's affordability and production of fewer GHG emissions. The remaining toxic CO is used as fuel to generate heat required for the chemical reaction. Figure 2 shows the typical life cycles of a common jet fuel produced from fossil fuels (such as jet fuel derived from crude oil) and a biofuel (such as biomass to liquid jet fuels).

Theoretically, jet fuels produced from biomass result in reduced CO_2 emissions across their entire life cycle. The CO_2 absorbed by plants during the growth of biomass is approximately equivalent to the CO_2 released into the atmosphere during

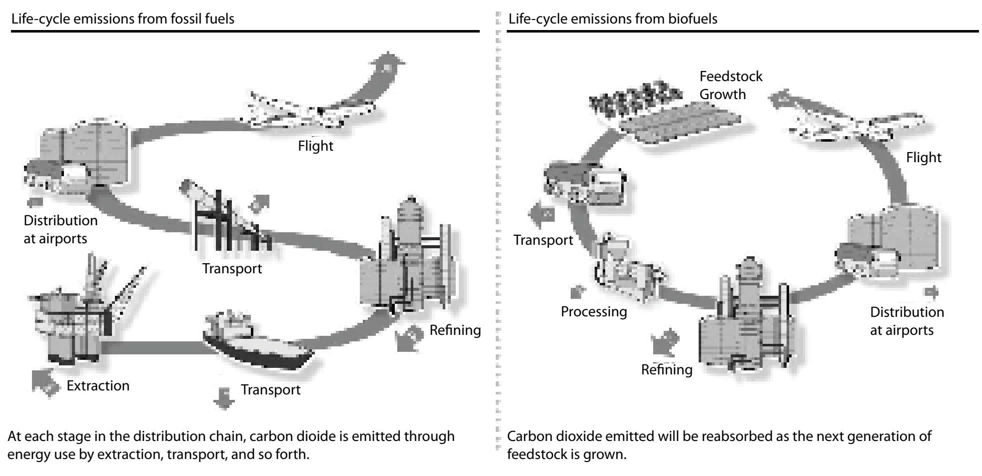

Figure 2. Life-cycle CO_2 emissions. (Reprinted by permission from Air Transport Action Group, *Beginner's Guide to Aviation Biofuels* [Geneva, Switzerland: Air Transport Action Group, May 2009], 3, http://www.enviro.aero/Content/Upload/File/BeginnersGuide_Biofuels_WebRes.pdf.)

burning of the biofuel. Although biofuels are not "carbon neutral" since it takes energy to run the equipment needed to grow, extract, transport, and process the biomass, the total amount of CO_2 released into the atmosphere by producing and using a biofuel is in theory significantly lower than that released into the atmosphere by a fuel produced from petroleum or other fossil fuels.[28] The alternative fuel we investigated (derived from a CBTL process) does not have the same carbon-neutral potential as one derived entirely from biomass because a large percentage of the CBTL-derived fuel is produced from coal; however, in theory, CBTL-derived jet fuels should affect the environment less than JP-8 because of the percentage of biomass they contain.

The life-cycle stages explored in our analysis included raw material extraction (mining/agriculture), raw material processing (refining/FT), and jet fuel use (burning fuel in flight) (see fig. 1). The transportation of material between these stages and its effects on the environment are captured internally by the EIO-LCA through economic interrelationships and incorporated into the total GWP of the GHG emission outputs at each stage. The authors assume that JP-8 and CBTL jet fuels emit the same total amount of GHGs in the jet-fuel-use LCA stage. According to the Energy Information Administration, the total GWP of the GHGs emitted during the use phase is typically 84 percent of the total GWP of the GHGs emitted during the entire life cycle for kerosene-based jet fuel.[29] We assume that the disposal phase does not exist since aircraft burn the fuel and nothing remains to dispose of after expending the energy source.

We need to make some caveats concerning our hybrid analytical model. The EIO-LCA database we used contained 2002 data, which may not reflect the economy of 2011.[30] Although a number of industries still use the same processes they employed in 2002, many have switched to more efficient ones that change their environmental footprint. For example, coal mining primarily uses the same technology today as it did in 2002, while vehicles such as the new hybrids are more efficient than standard fuel vehicles.[31] The accuracy and completeness of this database are thus uncertain, which translates into uncertainties in the EIO-LCA methodology. Additionally, the FT process to produce synthetic jet fuel was not available in 2002; therefore, the authors estimated the cost of producing CBTL fuels via the FT process to calculate their GWP due to GHGs. Despite these uncertainties in using EIO-LCA to compare JP-8 to CBTL, the process offers decision makers an approximation of the greener jet fuel for the environment.

To use the EIO-LCA model, one must first determine the cost of the resources required for the product, process, or service in the life-cycle stage under assessment. During this process, the EIO-LCA tool applies to the material-extraction phase of both fuels. For the material-processing phase, the EIO-LCA model applies only to the JP-8 jet fuel; the model does not apply to CBTL fuel because the FT synthesis process is not a standard industry in the United States. Therefore, no appropriate industry or sector exists to represent this stage in the EIO-LCA model. Finally, we did not include the jet-fuel-use LCA stage for both fuels because we assumed that the fuels have the same total GWP.

Costs for JP-8 Fuel

The total cost of a typical diesel fuel is the sum of four categories of costs. Using a retail price of $2.80 per gallon in October 2010, one finds that these categories included 17 percent for taxes, 12 percent for distribution and marketing, 6 percent for refining, and 65 percent for crude oil.[32] The authors estimated the cost associated with raw material extraction and processing for JP-8. Since the Air Force spent $6.7 billion on jet fuel in 2008, we estimate that the costs of raw material extraction (the value of the crude oil) and refining were approximately $4.4 billion and $402 million, respectively.[33] The detailed EIO-LCA database sectors that we selected for these costs were "oil and gas extraction" and "petroleum refineries."

Costs for Coal-Biomass-to-Liquid Fuel

The CBTL jet fuel we analyzed consisted of 8 percent (by weight) biomass and 92 percent (by weight) coal. Based on the Air Force's jet fuel use of 2.4 billion gallons in 2008, meeting the service's goal of "acquir[ing] 50% of the Air Force's domestic aviation fuel requirement via an alternative fuel blend" (mentioned above) equates to 600 million gallons of an alternative fuel.[34] Therefore about 550 million gallons of that amount would come from coal, and the remaining 50 million gallons would come from switchgrass. Since it takes about one-half of a short ton of coal to produce a barrel (42 gallons) of diesel fuel and one dry ton of switchgrass to produce one barrel of CBTL fuel, it would take about 6.5 million short tons of coal and 1.2 million dry tons of switchgrass to produce 1.2 billion gallons of jet fuel blend stock.[35] With coal selling for $42 per short ton as of January 2010 and switchgrass selling for $53 per dry ton, the total cost of raw material extraction is $273 million and $64 million, respectively.[36] The detailed EIO-LCA database sectors selected for these costs were "coal mining" and "all other crop farming." As previously mentioned, the EIO-LCA tool does not apply to the refining process; therefore, we obtained the environmental impacts from the Department of Energy.

To determine the environmental impact of each fuel, we summed the results for each life-cycle stage for each fuel. According to the EIO-LCA model results, the GWP for the CBTL fuel was 14 percent less than that for the JP-8 fuel, not considering carbon capture. In other words, the CBTL fuel emits 14 percent less GHGs, so it is greener. However, the Energy Independence Security Act of 2007 (EISA 2007) requires the life-cycle GWP of a prospective alternative jet fuel to be 20 percent less than the GWP of a petroleum-based jet fuel.[37] Since we found the CBTL's GWP to be only 14 percent less than the baseline amount, the CBTL without carbon capture does not qualify as an alternative fuel as defined by EISA 2007.

We also analyzed additional cases involving varying percentages of biomass, with and without carbon capture. Figure 3 presents the results, comparing the percent biomass used in CBTL with the greenness of CBTL compared to that of JP-8. The horizontal line at 20 percent represents the government standard set by EISA 2007. The dashed line shows the LCA results without considering carbon capture sequestration (CCS), while the solid line shows the results when including CCS. The figure shows that, without considering CCS (a more conservative assumption), the minimum amount of biomass to use in making CBTL fuel is 8–10 percent. In all cases, if CCS is considered,

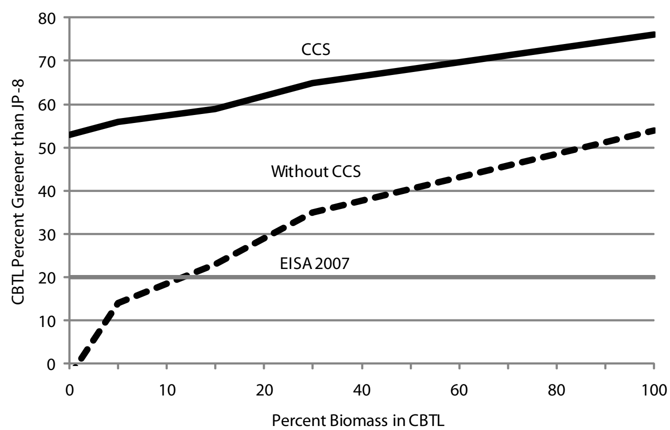

Figure 3. Percent biomass in CBTL versus CBTL percent greener than JP-8

then all CBTL fuels meet the EISA 2007 standard. At lower biomass percentages, the use of CCS significantly improves the greenness of CBTLs compared to that of JP-8.

Conclusion

Alternative fuels give the DOD options for fueling its extensive fleet of vehicles. The Air Force has embraced alternative fuels, which can fulfill the goal of the service's energy initiative (increasing the supply of fuel from domestic sources). However, determining the greenness of a fuel can prove difficult. Air Force decision makers must consider fuels that are comparable in cost and sustainability; furthermore, the fuels must lend themselves to production in significant quantities, have a life-cycle GHG footprint lower than that of petroleum-derived jet fuel (i.e., they are greener), and produce no degradation of flight safety.[38] Two issues arise in implementing an alternative fuel source. First, US regulations such as EISA 2007 demand that an alternative fuel have a total GWP 20 percent less than a baseline. Second, decision makers require an analytic method of evaluating the environmental impact of a fuel's life cycle.

This article demonstrated an analytical method that Air Force leaders can use to determine a fuel's greenness by comparing an alternatively produced jet fuel to a petroleum-derived one. As illustrated in figure 3 (above), the total GWP of all CBTL cases with and without simple CCS is less than the total for JP-8 jet fuel except for the case of 100 percent coal-to-liquid jet fuel without CCS. Therefore, according to an EIO-LCA analysis, the CBTL process produces a greener jet fuel over the entire life cycle. Consequently, we recommend that the Air Force use these alternative fuels as described in its energy strategy.

Air Force and DOD leaders may decide that strategic advantages of a US-made fuel source outweigh the need for an additional LCA. However, at a minimum, the Air Force should support additional field research to improve our understanding of the environmental impact of alternative fuel usage. Moreover, it should investigate the other portions of the supply chain that support aircraft fuels (such as fuel storage) to avoid any potential adverse, unintended consequences of using alternative fuels. ✪

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Notes

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9. MIL-HDBK-510-1, *Department of Defense Handbook: Aerospace Fuels Certification*, 13 November 2008, 10.
10. Tim Edwards, *Biomass-Derived Aviation Fuels*, internal document (Wright-Patterson AFB, OH: Air Force Research Laboratory, 2009), 2.

11. Ibid., 150. A flash point is the lowest temperature at which a flammable liquid releases sufficient vapors to be ignitable in air. Typical jet fuel has a flash point greater than 60° C while ethanol's flash point is less than 20° C. Heat of combustion is the amount of energy a given mass of a substance releases as heat during complete combustion with oxygen. Jet fuel has a heat of combustion greater than 40 (megajoules per kilogram [MJ/kg]) while ethanol yields less than 30 MJ/kg.

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